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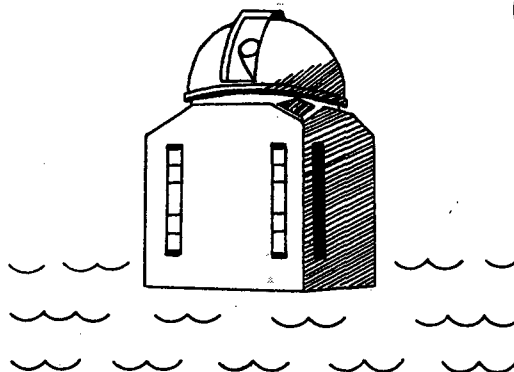
ABSOLUTE INTENSITY CALIBRATIONS OF
SOLAR K LINE PROFILES.

By

Jay M. Pasachoff

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ABSTRACT

Individual K-line profiles from elements of fine structure on the surface of the sun are calibrated absolutely. The continuum calibrations of Labs and Neckel and of Houtgast and Namba are considered, and the average K-profile is scaled to that of White and Suemoto.

The ranges of intensities across a high-resolution spectrogram are tabulated for various parts of the line profile. Although the spatially-averaged value for K_3 of 4.2% of the continuum corresponds to a brightness temperature of 4155°K, minimum and maximum values were 3980 and 4360°K, respectively. Similarly, K_{2v} ranges from 4200 to 4560°K, and K_{2r} from 4180 to 4460°K in small elements about 1 arc sec across.

I. INTRODUCTION

Studies of the surface of the sun often suffer from the sheer volume of data available. Yet as the only star on which many surface details can be observed, it is important to understand this single accessible example of the stars beyond. Even with the sun's great apparent brightness, current spectral observations expand both spatial and spectral dimensions until we are again limited by the amount of available light. Thus to gain precision in measuring the fluxes in different spectral lines, spatial information is often sacrificed by averaging over large areas.

A number of studies, including my own (Pasachoff, 1969a, 1969b, 1970), show that the fluctuations in the intensities and shapes of line profiles of elements of fine structure are so substantial that they cannot be ignored. My quantitative reduction was performed on spectrograms obtained with the McMath Solar Telescope at the Kitt Peak National Observatory by N. R. Sheeley. The 242 spectral profiles of individual elements of the sun were averaged to give a mean K-line profile which I scaled to match the photo-electric double-pass profile of White and Suemoto (1968). Their work is presented with respect to a calculated continuum value in that spectral region. The establishment of an absolute intensity scale for the mean profiles and for the line profiles for fine-structure elements is the subject of this paper. Such absolute values are important

for understanding the temperature structure of the sun and as a parameter in stellar atmospheres calculations. Previous research on the formation of the K-line has recently been reviewed by Linsky and Avrett (1970).

We shall use the following notation, slightly modified from that of Hale and Ellerman (1903), for the central parts of the K line. K_3 is the central dip; K_{2v} and K_{2r} are the small peaks on the violet and red sides of the line, respectively, and K_{1v} and K_{1r} are the dips just shortward of K_{2v} and longward of K_{2r} , respectively. The line wings, which extend for dozens of Angstroms, are often referred to in the literature as K_1 , the notation we have used for the dips. Here the wings have no specific names, although they would logically be called K_0 .

II. CALIBRATION OF THE ABSOLUTE INTENSITY SCALE

It is difficult to measure directly the absolute value of the flux in the centers of the H and K lines because of the uncertainties in the transmissions of the earth's atmosphere and in the instrumentation. Further, no satisfactory continuum exists nearby in the spectrum with which one could compare. The problem is further complicated by the relative importance of scattered light, for 1 per cent of the continuum is equivalent to 25 per

cent of the central intensity of the K line.

Only recently have we fully appreciated the importance of the variations in instrumental and atmospheric sensitivity through this region of the ultraviolet spectrum (Linsky, 1968; Pasachoff, Noyes and Beckers, 1968; White and Suemoto, 1968; Pasachoff 1969b). Thus the basic work of Goldberg, Mohler and Müller (1959, revised by Teske [1967]), which was calibrated on the 4000 Å window alone, has been superseded.

The White and Suemoto calibration is based on the work of Michard (1950), which indicates that the observed continuum near 3900 Å is depressed by 15 per cent, and the work of Beckers (1962), which indicates that the observed continuum near 3953 Å is depressed by 16.3 per cent. A smooth curve is drawn through these corrected points and through supposed windows between 4000 Å and 4050 Å. Carbon, Gingerich and Kurucz (1968) have found that the 4000 Å window (actually 3999.89 Å) has a contribution from line blanketing less than 1 per cent. White and Suemoto make a consistency check of this continuum that is good to about 5 per cent.

Zirker (1968) accepts the uncorrected intensity peaks at 3909 Å and 4013 Å as a continuum, and draws a straight line between them on the tracings to represent a continuum level with which to compare the intensity at each point.

He assigns a color temperature of 6500°K to this continuum, fixed at the 4013 Å point (Zirker, 1969), to give absolute intensities. The error at 3909 Å is small, $\Delta \log I = 0.013$.

Zirker compares his values with those of Houtgast (1965, 1968) and finds that

$$\Delta \left[\log \frac{I_{\lambda}}{I_{4013.4}} \right]_{\text{Houtgast-Zirker, maximum}} = 0.052$$

and is about 0.02 near the centers of the H and K lines. Figure 1 shows the trend of the disparity between the measures of Houtgast and Zirker. $\log (I_{\text{Houtgast}}/I_{\text{Zirker}})$ varies roughly linearly from -0.05 at 3900 Å to +0.01 at 4000 Å, i.e. $(I_{\text{Houtgast}}/I_{\text{Zirker}}) = 0.891$ at 3900 Å and 1.025 at 4000 Å, a variation of over 10 per cent. Zirker finds agreement between his I/I_C values and those of White and Suemoto for $\mu < 0.7$, but they have used different continua.

Linsky (1968) finds that $I(K_3)/I(H_3) = 1.061$ and 1.041 for his two observing days, compared with White and Suemoto's value of 1.00 and Zirker's value of 1.075. Linsky accepts the observed continuum at 4000 Å as a window, and follows typical values from his model atmospheres in assigning a drop of 2.2 per cent in the continuum to 3968 Å, and 4.4 per cent from 4000 Å to 3933 Å. His results for the absolute values of the intensities of the cores at $\mu = 1$ are 4.34 per cent and 4.09 per

cent of the continuum for H_3 and K_3 respectively.

The Utrecht Atlas (Minnaert, Mulders and Houtgast, 1940) presents tracings of the H and K lines with respect to a value, not necessarily the continuum, set equal to 100. This 100-level is merely approximately set to provide full-scale deflections for the lines in a moderate spectral region. The value for the center of the K line is about 6.5 on this scale.

There is undoubtedly a major contribution from stray light in the spectra traced for the Utrecht Atlas, and it is unfortunate that we must refer to it for intensity information in the cores of strong lines. Since it is a standard reference, however, several studies of the continuum in this region have referred to it.

Recent contributions to the absolute calibration of the continuum have been made by Labs and Neckel (1968) and Houtgast and Namba (1968). They use their absolute intensity data to calibrate each tracing in the Utrecht Atlas.

Labs and Neckel feel that their measured continuum intensities agree with recent model continua above 4000 Å to within 2 per cent, but are more reticent about values below 4000 Å. They estimate from the scatter that the error for the calibration of the tracings in the Utrecht Atlas is about 3 to 4 per cent from 3600 Å to 4200 Å. The points of Labs and Neckel and their adopted curve lie

slightly below those of Houtgast (1965) from 3400 Å to 3500 Å and slightly above (averaging perhaps 0.02 in the logarithm) from 3600 Å to 4100 Å.

Labs and Neckel give the intensity value, in $w \text{ cm}^{-1} \text{ ster}^{-1} \text{ Å}^{-1}$, for Atlas level 100 (which is not necessarily the theoretical continuum level). A 4 per cent error in the 100-level would mean about an 0.25 per cent error at the center of K. Since the values from the Utrecht Atlas are severely affected by scattered light at the center of the K line, we used the following procedure to calibrate the data described in this paper:

For many wavelengths between 3900 Å and 4000 Å, we computed the absolute intensity as the product of the value we measured in the Utrecht Atlas as a fraction of the 100-level and the absolute value for the 100-level interpolated in the values of Labs and Neckel. This should be equal to the residual intensity given by White and Suemoto times the absolute value of their continuum. That is:

$$\alpha_{\text{Utrecht}} I_{\text{L\&N; Utrecht}}^{100} = r_{\text{W\&S}} C_{\text{W\&S}}.$$

$C_{\text{W\&S}}$ is graphed in Figure 2. Discarding the points near the centers of H and K where stray light is a major contributor, we adopt the value $C_{\text{W\&S}} = (4.5 \pm 0.1) \times 10^6 \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \text{ Å}^{-1}$ for the continuum. This agrees, within

our limits of error, with the continuum value deduced by Houtgast and Namba (1968).

The central intensity of White and Suemoto, $r_K = 4.2$ per cent, then corresponds to the absolute value 1.9×10^5 erg cm⁻²sec⁻¹ster⁻¹Å⁻¹. The rest of the profile can be similarly calibrated. We use the White and Suemoto values for the line profiles, as the Utrecht Atlas values near line center are greatly affected by scattered light.

We can assign brightness temperatures, T_b , by the Planck function in units of erg cm⁻²sec⁻¹ster⁻¹Å⁻¹,

$$(1) \quad B_\lambda d_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda kT_b) - 1} = 1.27 \times 10^9 \frac{1}{\exp(3.66 \times 10^4/T)} d\lambda.$$

The scale is shown on the right-hand axis of Figure 3, which shows our mean profile scaled to match that of White and Suemoto. The average value of K_3 corresponds to $(4155 \pm 25)^\circ\text{K}$.

In this analysis, we were forced to go through the extra steps of referring to the continuum and to the Utrecht Atlas only because other works refer to them. It would be useful if observers rather than or in addition to referring to a continuum, would refer to the intensity of some identifiable peak in the wavelength range under consideration. This might be the window at 3999.9 Å, or even the lower peak at 3950 Å. New studies could thus draw on earlier work more readily.

III. INTENSITY FLUCTUATIONS

We have presented graphs of the fluctuations in intensity (Pasachoff, 1970) for the various K_1 . Those graphs covered only half the data summarized in Table I, which shows the ranges of values. Equation 1 has been used to translate those values into equivalent black body temperatures. Thus we see that the value of the K_3 minimum, sometimes quoted to hundredths of a per cent, actually varies in our data from 2.8 per cent up to 6.2 per cent, equivalent to a variation of the equivalent black body temperature of 380°K from 3980°K to 4360°K.

Similarly, K_{2v} varies from 4200°K to 4560°K, and K_{2r} from 4180°K to 4460°K. As we have previously discussed in detail, all these fluctuations are not well correlated.

Theoretical calculations of stellar atmospheres that compute absolute intensity values and try to deduce physically-meaningful temperatures in the region of the temperature minimum must take these fluctuations into account.

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this aspect of the field.

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TABLE I
Fluctuations in the K line.

	Low		High		Rms Deviation I (%)	Range T_b (°K)
	I (%)	T_b (°K)	I (%)	T_b (°K)		
K_{1v}	4.2	4160	7.5	4460	0.59	300
K_{2v}	4.5	4200	9.1	4560	0.60	360
K_3	2.8	3980	6.2	4360	0.49	380
K_{2r}	4.3	4180	7.5	4460	0.58	280
K_{1r}	3.9	4130	6.9	4410	0.56	280

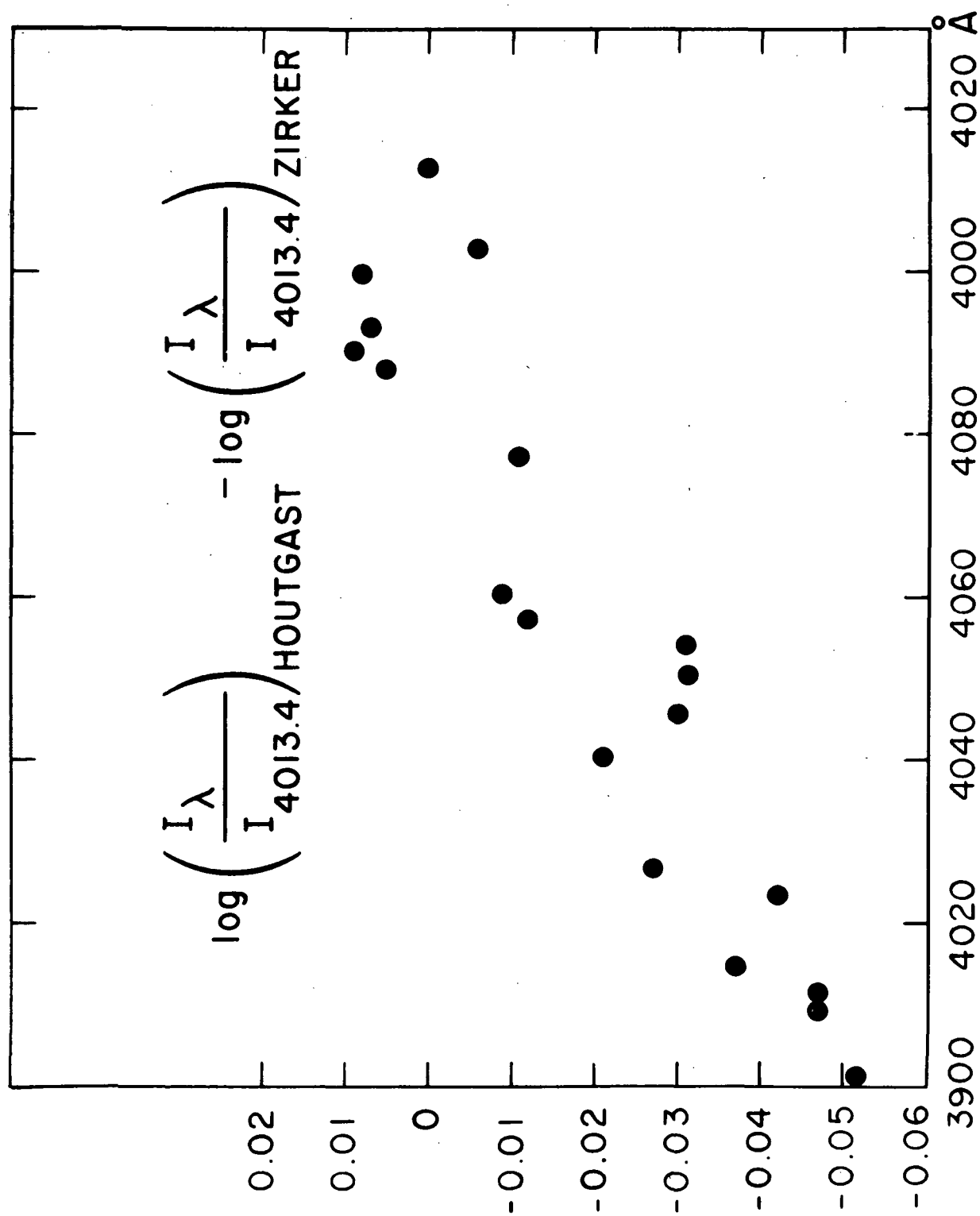


Figure 1. Comparison of the calibrations of Houtgast (1965) and Zirker (1968).

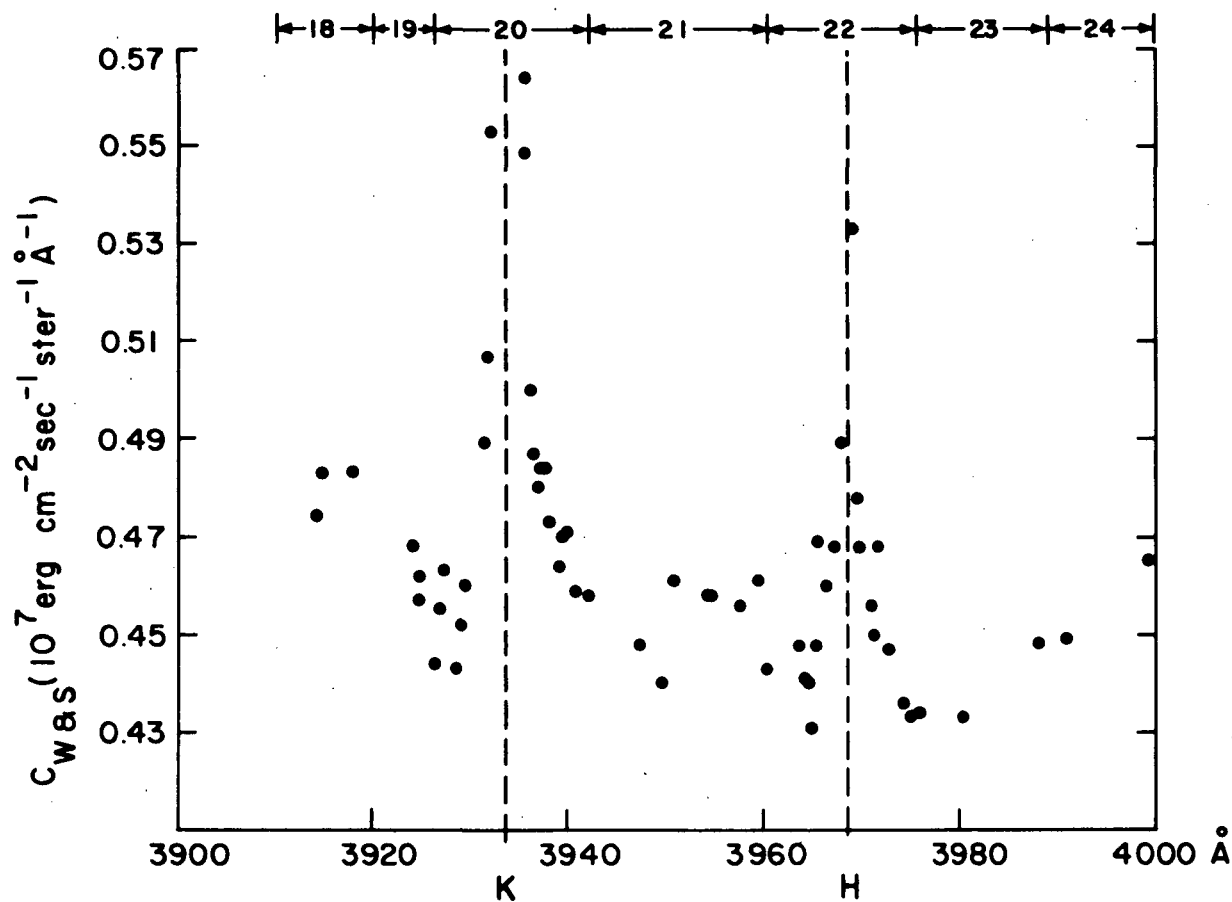


Figure 2. The effective value of the continuum as a function of wavelength in the region of the H and K lines. Discarding the points near H and K where the contribution of scattered light is important, we adopt the value $(4.5 \pm 0.1) \times 10^6 \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \text{ Å}^{-1}$.

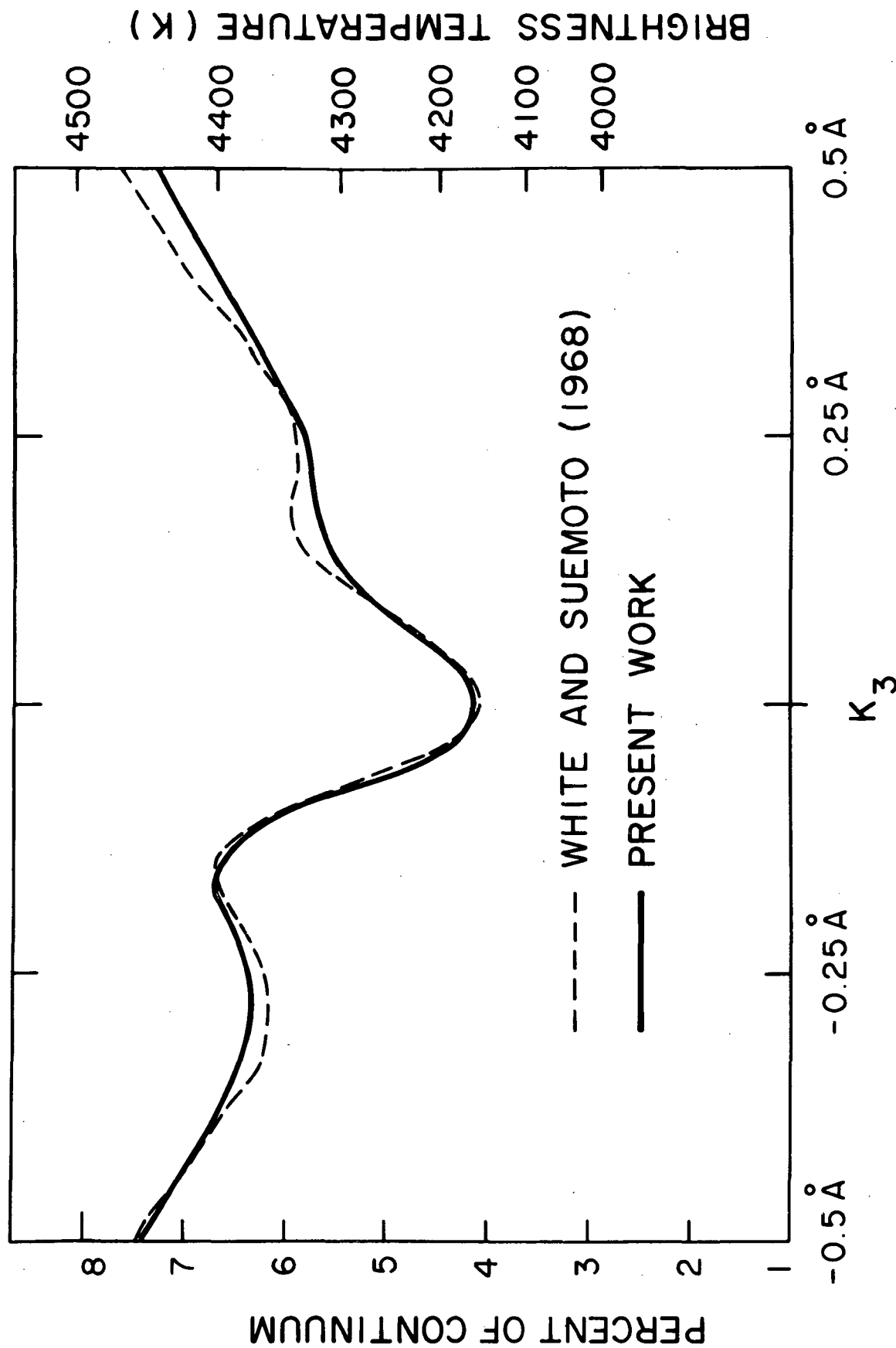


Figure 3 Comparison of the low-resolution K-line profiles of White and Suemoto (1968) and the spatial average of the fine structure profiles described in Pasachoff (1970), calibrated in terms of brightness temperature.